УДК 539.172.4+539.166

I. M. Kadenko[1], V. A. Plujko[1], B. M. Bondar[1,2],
O. M. Gorbachenko[1], B. Yu. Leshchenko[1,3], K. M. Solodovnyk[1]

[1] *Nuclear Physics Department, Taras Shevchenko National University, Kyiv*
[2] *All-Ukrainian Center for Radiosurgery of the Clinical Hospital "Feofania", Kyiv*
[3] *National Technical University of Ukraine "Kyiv Polytechnic Institute", Kyiv*

GAMMA-RAYS FROM natSn AND natC INDUCED BY FAST NEUTRONS

The cross-sections of prompt gamma-ray production from natSn and natC elements induced by 14.1-MeV neutrons were measured. The time-of-flight technique was used for n-γ discrimination. The experimental results were compared with theoretical calculations performed by Empire 3.2 and Talys 1.6 codes using different models for photon strength function and nuclear level density.

Keywords: fast neutrons, prompt gamma-rays, time-of-flight technique, Empire 3.2 and Talys 1.6 codes, photon strength function, nuclear level density.

Introduction

Modern developments of nuclear fusion technologies require new nuclear data and refinements of existing data on DT-neutrons interactions [1]. For radiation damage and gamma-ray shielding calculations, it is necessary to know the cross-sections of (n, xγ) reactions. Apart from practical applications, the gamma-ray spectra can also give information about the nuclear structure, excited states, their population and decay. Furthermore, the comparison of experimental results with corresponding theoretical calculations enables to analyze different theoretical approaches describing nuclear reaction mechanisms and to study a reliability of different calculations codes for estimations of the gamma-ray productions.

Experimental results

The amplitude spectra of gamma-rays were measured in a circular geometry using time-of-flight technique based on pulse neutron generator (NPG-200), designed and manufactured at Nuclear Physics Department of Taras Shevchenko National University of Kyiv. The neutron intensity was ~10^7 n/s with pulse frequency 7.25 MHz. Investigated samples of natSn and natC with masses $m_{Sn} = 3208$ g, $m_C = 1600$ g were irradiated by neutrons with the energy of $E_n = 14.1 \pm 0.2$ MeV, the gamma-ray emission angle θ_γ was near 90°. The flight pass, the time window and the detection threshold were equal to 176 cm, 20 ns and 2 MeV, respectively. This provided reliable separation of prompt gamma-rays from neutron and γ-background. The detection of prompt gamma-rays was done using NaI(Tl) scintillator of sizes $\varnothing 2r_d \times h_d \equiv 150 x 100$ mm surrounded by Geiger-counters. The pulses from NaI(Tl) and Geiger counters were in anti-coincident mode for reducing the influence of cosmic rays background, that enables to perform measurements in a wide energy range from 2 MeV and up to ~18 MeV. This technique of background reduction was of special importance for high-energy range (>14 MeV), where detected gamma-rays appear only from (n, γ) reactions and have very low intensities. The full description of experimental set-up and data acquisition system is presented in Ref. [2].

As an example, in Fig. 1 the measured amplitude spectrum $S_\gamma(\varepsilon)$ of gamma-rays emitted at the angle $\theta_\gamma = 90^\circ$ from natSn(n, xγ) reactions is presented as a function of number of pulse amplitude channel (upper scale) or the energy loss of gamma-rays (ε) in the detector volume (lower scale).
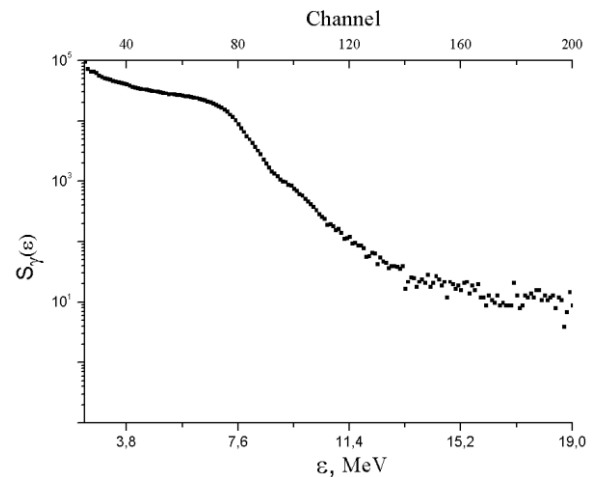

Fig.1. Amplitude spectrum of γ-rays from natSn (n, xγ) reactions with 14.1 MeV neutrons: ε is the energy deposited in the detector.

The value of the double differential cross section $d^2\sigma_\gamma / dE_\gamma d\Omega_\gamma \equiv \sigma_\gamma(E_\gamma, \theta_\gamma)$ from (n, xγ) reactions is unfolded from amplitude spectra by numerical method of approximate solution of ill-posed problem

on the compact set [2 - 4]. Namely, the differential cross section $\sigma_\gamma(E_\gamma, \theta_\gamma)$ is obtained from amplitude spectra $S_\gamma(\varepsilon)$ by solving the following integral equation

$$S_\gamma(\varepsilon) = \int_0^{E_{max}} \chi_S(\varepsilon, E_\gamma)\sigma_\gamma(E_\gamma, \theta_\gamma)dE_\gamma , \qquad (1)$$

with $\chi_S(\varepsilon, E_\gamma)$ for the total response function of the spectrometer function with NaI(Tl) response function from Ref. [5], ε for the γ-ray energy deposited in the detector volume and E_γ for the γ-ray energy with maximal value E_{max}. This equation is presented then in the matrix form

$$\vec{S} = X \cdot \vec{\sigma} . \qquad (2)$$

Here, $\vec{S}$, $\vec{\sigma}$ are the vectors with elements $S_i = S_\gamma(\varepsilon_i)$, $\sigma_j = \sigma_\gamma(E_{\gamma,j}, \theta_\gamma)$, X is rectangular matrix with elements $X_{i,j} = \chi_S(\varepsilon_i, E_{\gamma,j})\Delta E_\gamma$ ($i = 1, ..., m$; $j = 1, ..., n$), m is number of bins in the amplitude spectra and n is the number of energy intervals; $\Delta E_\gamma \sim 0.5$ MeV is the width of the gamma-ray bins; $E_{\gamma,j}, \varepsilon_i$ are the values of the corresponding energies in the bins.

The linear algebraic equation (2) was solved by the least squares method to search for a minimum of the square of norm of the residual $\vec{r}(\vec{\sigma}) = X \cdot \vec{\sigma} - \vec{S}$,

$$Min\left\{\|\vec{r}(\vec{\sigma})\|^2 = \vec{r}^T \cdot \vec{r} = \left(X \cdot \vec{\sigma} - \vec{S}\right)^T \cdot \left(X \cdot \vec{\sigma} - \vec{S}\right)\right\}, \qquad (3)$$

where symbol "T" denotes transpose. For determination of $\vec{\sigma}$, the iteration algorithm of the steepest descent method was used in the form

$$\vec{\sigma}_{k+1} = \vec{\sigma}_k - 2\lambda_k \cdot X^T \cdot \vec{r}_k ,$$

$$\vec{r}_k = \vec{r}(\vec{\sigma}_k) = X\vec{\sigma}_k - \vec{S} . \qquad (4)$$

Value of the parameter λ_k was found from condition of minimization the square of the residual norm

$$Min\left\{\|\vec{r}_{k+1}\|^2\right\},$$

$$\vec{r}_{k+1} = (1 - 2\lambda_k \cdot X \cdot X^T) \cdot \vec{r}_k . \qquad (5)$$

As a zero approximation ($\vec{\sigma}_o$), the results of calculations by Empire code with default input parameters were used. The iteration procedure was stopped at a condition $(\|\vec{\sigma}_{k+1}\|^2 - \|\vec{\sigma}_k\|^2) \leq 0.01 \cdot \|\vec{\sigma}_k\|^2$. The uncertainties of unfolded cross sections were evaluated from variation of amplitude spectra in the assumption of Gauss distribution of amplitude spectrum uncertainties due to the large number of independent external factors.

Fig. 2 shows the experimental unfolded cross sections and its uncertainties in comparison with the experimental data from EXFOR database (Refs. [6 - 10]). Here our results and experimental data from Refs. [6 - 10] are multiplied, like in Ref. [2], by factor 4π; that is, they are considered as the angle integrated differential cross section (gamma-ray spectrum $d\sigma_\gamma(E_\gamma) / dE_\gamma = \int d\Omega_\gamma \sigma_\gamma(E_\gamma, \theta_\gamma) = 4\pi\sigma_\gamma(E_\gamma, \theta_\gamma)$) for ^{nat}Sn (Fig. 2, *a*), and as the total cross section $\sigma_\gamma(E_n) = 4\pi\int dE_\gamma \sigma_\gamma(E_\gamma, \theta_\gamma)$ of gamma-emission at $E_n = 14.1$ MeV for ^{nat}C (Fig. 2, *b*) due to weak dependence of the differential cross sections on gamma-emission angle.
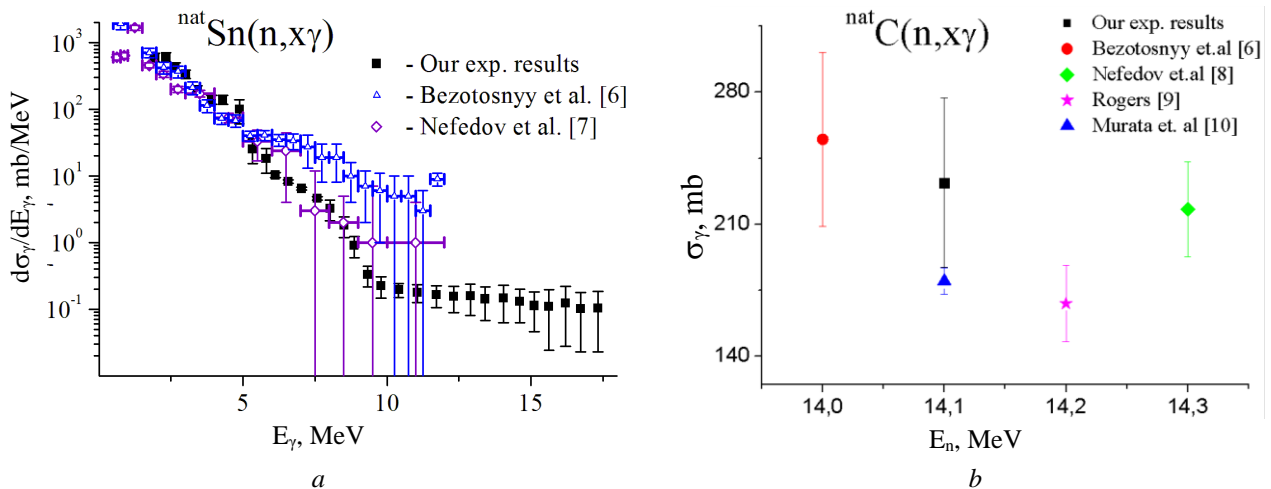

Fig. 2. The cross sections of gamma-ray emission: the differential cross section $d\sigma_\gamma / dE_\gamma$ of gamma-ray emission from ^{nat}Sn (*a*), and the total cross section $\sigma_\gamma(E_n)$ of gamma-rays from ^{nat}C near $E_n = 14.1$ MeV (*b*).

Note that we were able to observe γ-transitions for ^{nat}Sn in the range $E_\gamma \geq 2$ MeV and for ^{nat}C only from the first excited level with $E_\gamma = 4.43$ MeV due to low intensities of gamma-transitions with other energies.

As one can see from Fig. 2, *a*, the differential cross section $d\sigma_\gamma / dE_\gamma$ for ^{nat}Sn smoothly decreases with energy and has nearly constant value in the energy interval $12 \div 18$ MeV, where it was measured for the first time. Transition with $E_\gamma = 4.43$ MeV from the first excited level of ^{12}C to the ground state is dominated. It allowed us to determine cross-section of $(n, x\gamma)$ reactions for ^{nat}C (i.e., $^{12}C(n, n'\gamma)^{12}C$ and $^{13}C(n, 2n\gamma)^{12}C$) by measurements of intensity of this transition with the result $\sigma_\gamma(E_n) = 232 \pm 30$ mb at $E_n = 14.1$ MeV, which is in good agreement with the results of other authors (see Fig. 2, *b*).

Theoretical calculations and data analysis

The differential cross section $d\sigma_\gamma / dE_\gamma$ for the target with natural elements is a sum of the differential cross-sections for each isotope A_i, Z_i of the target

$$d\sigma_\gamma / dE_\gamma = \sum_i w_i \cdot \sum_x d\sigma(A_i(n, \{x, \gamma\})) / dE_\gamma,$$

$$w_i = \alpha_i / 100, \qquad (6)$$

where α_i is the abundance of the isotope A_i, Z_i and $d\sigma(A_i(n, \{x, \gamma\})) / dE_\gamma$ is the differential cross sections of gamma-ray emission from all possible reactions $(n, \{x, \gamma\})$ with any outgoing particle (x) and gamma-rays. Calculations were performed using the EMPIRE 3.2 and TALYS 1.6 codes [11, 12] with allowance for outgoing particles and gamma-rays at equilibrium (HF curves in the figures) and from preequilibrium states using the default sets of the input parameters, specifically, for EMPIRE code, these parameters are Modified Lorentzian model (MLO1) for the electric dipole photon strength function (PSF) and Enhanced Generalized Super-Fluid Model (EGSM) for nuclear level density (NLD). Calculations were performed with preequilibrium processes (PE) (parameter PCROSS = 1.5) and without PE (PCROSS = 0). For TALYS code, default parameters are Enhanced Generalized Lorentzian (EGLO) for PSF and Gilbert - Cameron approach (GC) for NLD. Global optical potential given by Koning - Delaroche [13] was adopted as default in the calculations within two codes. The following values of abundances were used [14]: ^{116}Sn (14.54 %), ^{117}Sn (7.68 %), ^{118}Sn (24.22 %), ^{119}Sn (8.59 %), ^{120}Sn

(32.58 %), ^{122}Sn (4.63 %), ^{124}Sn (5.79 %) for ^{nat}Sn target, and ^{12}C (98.89 %), ^{13}C (1.11 %) for ^{nat}C target, where abundance is indicated in brackets.

Fig. 3 and Table 1 show comparison of the theoretical calculations with the experimental data. One can see that theoretical calculations as a whole are rather good estimates the experimental data. For Sn nuclei, preequilibrium processes are strongly affected by emission of gamma-rays of high energies and should be taken into account for gamma-spectrum calculations.
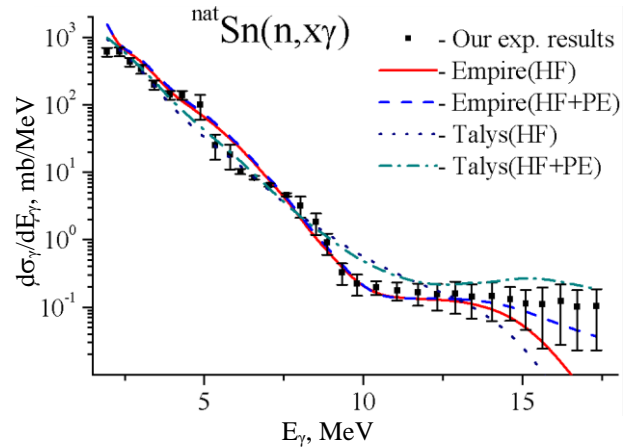

Fig. 3. Comparison of experimental data with calculations of gamma-ray spectrum from (n, xγ) reactions on ^{nat}Sn.

Table 1. **Comparison of experimental data with calculations by EMPIRE of inclusive (n, xγ) cross section for ^{nat}C at $E_n = 14.1$ MeV**

Cross-sections	σ_γ, mb
Our experimental data	232 ± 30
Calculations without PE	204
Calculations with PE	203

Next is considered a sensitivity of the calculated gamma spectra to the PSF and the NLD models; for this aim, we performed the calculations within EMPIRE code with allowance for preequilibrium processes (PCROSS = 1.5). The results are shown in Fig. 4 and Table 2. In the calculations of the curves on Fig. 4, *a*, the EGSM is taken for nuclear level density and different approaches are used for PSF [14 - 16]: Standard Lorentzian model (SLO), MLO1 and MLO4 variants of Modified Lorentzian (MLO) approach, Enhanced Generalized Lorentzian (EGLO) model (according to RIPL-2) and Generalized Fermi Liquid (GFL) model. In the results presented in Fig. 4, *b*, the model MLO1 is used for PSF and different methods are taken for NLD [14, 17]: the Generalized Superfluid model (GSM), Gilbert and Cameron (CG) model, microscopic combinatorial level densities within Hartree - Fock - Bogoliubov method (HFBM) and Modified Generalized Super-Fluid model with Bose attenuated numbers for vibrational enhancement factor (MEGSM).
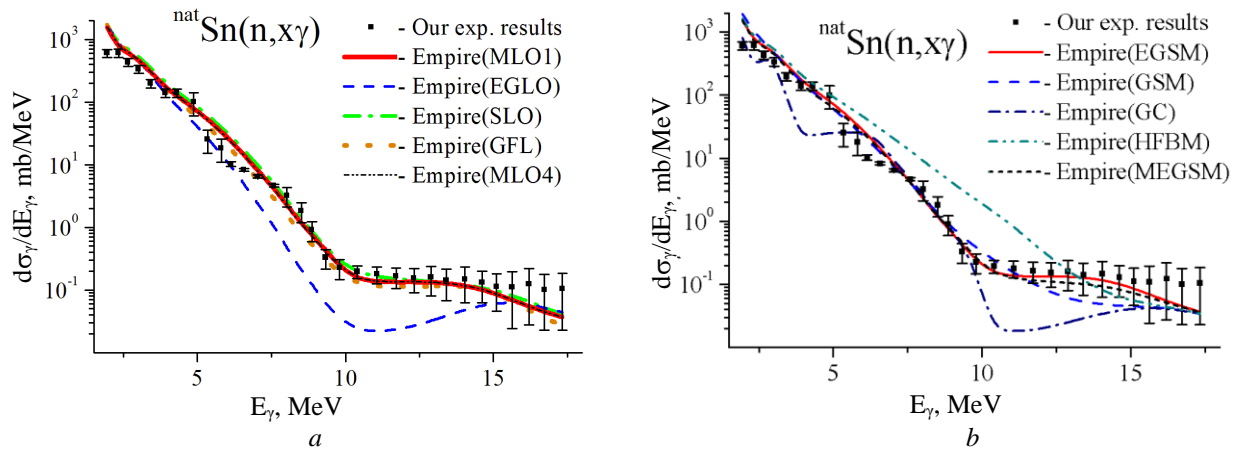
Fig. 4. Experimental data and corresponding theoretical calculations of (n, xγ) cross sections for natSn performed using different models for PSF (*a*) and NLD (*b*).

Table 2. **Comparison of experimental data and theoretical calculations of (n, xγ) cross sections at E_n = 14.1 MeV for natC using different models of PSF and NLD**

Cross sections		σ_γ, mb
Our experimental data		232 ± 30
Theoretical calculations	NLD: EGSM PSF: MLO1, EGLO, SLO, GFL, MLO4	203
	PSF: MLO1 NLD: EGSM, MEGSM	203
	PSF: MLO1 NLD: HFBM, GC	252

It can be seen from results in Fig. 4, the calculated cross sections are weakly dependent on PSF shape except for EGLO model for which we obtained much lower values of gamma-spectrum in the 6 - 15 MeV energy range in comparison with the data. The sensitivity of the calculations to the NLD models is much stronger than to the PSF. Considerable disagreement is demonstrated between data and calculated cross sections with HFBM and GC in the energy ranges 5 - 12 MeV and 3 - 6 MeV, 10 - 15 MeV respectively. Theoretical cross section of (n, xγ) reaction on natC for gamma rays of 4.43 MeV is only weakly dependent on PSF shape.

Conclusions

The yield of prompt γ-rays produced by interaction of the 14.1 MeV neutrons with natSn and natC targets were measured using the time-of-flight technique, and cross sections of (n, xγ) reactions were unfolded from amplitude spectra. Determined cross-sections are in a rather good agreement with the data of other experiments [6 - 10]. For the high energy range (12 ÷ 18 MeV), the differential cross section of (n, xγ) reactions on natSn were measured for the first time and corresponding values are approximately equal to 0.10 ÷ 0.13 mb/MeV.

Comparisons of the experimental data with the calculations demonstrate high reliability of the calculations with the use of the EMPIRE and TALYS codes [11, 12] with the default sets of the input parameters for estimations of the gamma-ray spectrum in reactions induced by fast neutrons.

REFERENCES

1. *Forrest R.A.* Nuclear data for fusion applications // Proc. Int. Conf. on Nucl. Data for Sci. and Technol. (ND2007), (Nice, France, May 22 - 27, 2007). - Nice, 2007. - P. 11 - 16.

2. *Kadenko I.M., Plujko V.A., Bondar B.M. et al.* Prompt gamma-rays from fast neutron capture in natNi // Nucl. Phys. At. Energy. - 2016. - Vol. 17, No. 2. - P. 122 - 129.

3. *Tikhonov A.N., Goncharsky A.V., Stepanov V.V. et al.* Numerical methods for the solution of ill-posed problems. - Moskva, 1995. - 253 p.

4. *Kabanikhin S.I.* Inverse and Ill-Posed Problems // Novosibirsk: Sibirskoe nauchnoe izdatelstvo. - Novosibirsk, 2009. - P. 60 - 63 (in Russian).

5. *Gurevich G.M., Mazur V.M., Solodukhov G.V.* Apparatus function of scintillation γ-spectrometer based on large NaI(Tl) detector // Instruments and Experimental Techniques. - 1975. - Vol. 2. - P. 59 - 62 (in Russian).

6. *Bezotosnyy V.M., Gorbachev V.M., Surov L.M., Shevtsov M.S.* Total cross-section for gamma-production by inelastic interaction of fast neutrons with light, intermediate and heavy nuclei // Voprosy atomnoj nauki i tekhniki. Ser. Yadernye konstanty. - 1978. - Iss. 3(30). - P. 21 (in Russian); EXFOR subentry #40516052, #40516009.

7. *Nefedov Yu.Ya., Nagornyj V.I., Semenov V.I. et al.* Gamma-ray production cross-section and spectrum

measurement results for inelastic interaction of 14 MeV neutrons with nuclei of Na, S, Cl, Ti, V, Cr, Ni, Zn, Ge, Nb, Cd, In, Sn, Bi, 235U and 238U // Voprosy atomnoj nauki i tekhniki. Ser. Yadernye konstanty. - 2000. - Iss. 1. - P. 7 (in Russian); EXFOR subentry #41379014.

8. *Nefedov Yu.Ya., Nagornyj V.I., Semenov V.I. et al.* Results of measurements of gamma-ray production cross-sections and spectra in inelastic interaction of 14 MeV neutrons with nuclei C, O, Mg, Al, Fe, Cu, Zr, Mo, W, Pb // Proc. of Ninth Intern. Conf. on Radiation Shielding (Tsukuba, Japan, October 17 - 22, 1999). - Tsukuba, 1999. - P. 692 - 696; EXFOR subentry #41333012.

9. *Rogers V.C., Orphan V.J., Hoot C.G., Verbinski V.V.* Gamma-Ray Production Cross Sections for Carbon and Nitrogen from Threshold to 20.7 MeV // Nuclear Science and Engineering. - 1975 - Vol. 58. - P. 298; EXFOR subentry #10490003.

10. *Murata I., Yamamoto J., Takahashi A.* Differential cross-sections for gamma-ray production by 14-MeV neutrons with several elements in structural materials // Conf. on Nucl. Data for Science and Technol. (Mito, Japan, 1988). - Mito, 1988. - P. 275; EXFOR subentry #22096009.

11. *Herman M., Capote R., Carlson B.V. et al.* EMPIRE: Nuclear Reaction Model Code System for Data Evaluation // Nuclear Data Sheets. - 2007. - Vol. 108. - P. 2655 - 2715; URL: http://www.nndc.bnl.gov/empire/

12. *Koning A.J., Hilaire S., Duijvestijn M.C.* TALYS-1.0 // Proc. of the Intern. Conf. on Nuclear Data for Science and Technology, ND2007 (Nice, France, April 22 - 27, 2007). - Nice, 2007. - P. 211 - 214; URL: http://www.talys.eu/

13. *Koning A.J., Delaroche J.P.* Local and global nucleon optical models from 1 keV to 200 MeV // Nucl. Phys. - 2003. - Vol. A713. - P. 231 - 310.

14. *Capote R., Herman M., Oblozinsky P. et al.* Parameters for calculation of nuclear reactions of relevance for energy and non-energy nuclear applications // Nuclear Data Sheets. - 2009. - Vol. 110. - P. 3107 - 3214; URL: http://www-nds.iaea.org/RIPL-3/

15. *Plujko V.A., Capote R., Gorbachenko O.M.* Giant Dipole Resonance parameters with uncertainties from photonuclear cross sections // Atomic Data and Nuclear Data Tables. - 2011. - Vol. 97. - P. 567 - 589.

16. *Plujko V.A., Gorbachenko O.M., Rovenskykh E.P., Zheltonozhskii V.A.* Average description of dipole gamma transitions in hot atomic nuclei // Nuclear Data Sheets. - 2014. - Vol. 118. - P. 237 - 239.

17. *Plujko V.A., Gorbachenko O.M., Bondar B.M., Rovenskykh E.P.* Nuclear level density within extended superfluid model with collective state enhancement // Nuclear Data Sheets.- 2014. - Vol. 118. - P. 240 - 242.

І. М. Каденко[1], В. А. Плюйко[1], Б. М. Бондар[1,2],
О. М. Горбаченко[1], Б. Ю. Лещенко[1,3], К. М. Солодовник[1]

[1] *Київський національний університет імені Тараса Шевченка, Київ*
[2] *Всеукраїнський центр радіохірургії клінічної лікарні «Феофанія», Київ*
[3] *Національний технічний університет України «Київський політехнічний інститут», Київ*

ГАММА-ВИПРОМІНЮВАННЯ З natSn ТА natC ПІД ДІЄЮ НЕЙТРОНІВ

Виміряно перерізи утворення миттєвих гамма-квантів при взаємодії 14-MeB нейтронів із natSn та natC. Для розділення n-γ сигналів було застосовано методику часу прольоту. Експериментальні результати порівняно з відповідними теоретичними розрахунками, виконаними за допомогою кодів Empire 3.2 та Talys 1.6 із застосуванням різних моделей для фотонних силових функцій та густини ядерних рівнів.

Ключові слова: швидкі нейтрони, миттєві гамма-кванти, методика часу прольоту, коди Empire 3.2 і Talys 1.6, фотонна силова функція, густина ядерних рівнів

И. Н. Каденко[1], В. А. Плюйко[1], Б. М. Бондар[1,2],
А. Н. Горбаченко[1], Б. Ю. Лещенко[1,3], Е. Н. Солодовник[1]

[1] *Киевский национальный университет имени Тараса Шевченко, Киев*
[2] *Всеукраинский центр радиохирургии клинической больницы «Феофания», Киев*
[3] *Национальный технический университет Украины «Киевский политехнический институт», Киев*

ГАММА-ИЗЛУЧЕНИЕ ИЗ natSn И natC ПОД ДЕЙСТВИЕМ НЕЙТРОНОВ

Измерены сечения образования мгновенных гамма-квантов при взаимодействии 14-МэВ нейтронов с natSn и natC. Для разделения n-γ сигналов использована методика времени пролета. Экспериментальные результаты сравниваются с соответствующими теоретическими расчетами, выполненными при помощи кодов Empire 3.2 и Talys 1.6 с использованием различных моделей для фотонных силовых функций и плотности ядерных уровней.

Ключевые слова: быстрые нейтроны, мгновенные гамма-кванты, методика времени пролета, коды Empire 3.2 и Talys 1.6, фотонная силовая функция, плотность ядерных уровней.